Zeitschrift: IABSE congress report = Rapport du congrès AIPC = IVBH Kongressbericht

Band: 14 (1992)

Artikel: Studies on aseismic measures for a large existent sluice lock

Autor: Gao, Ming / Dai, G.Y.

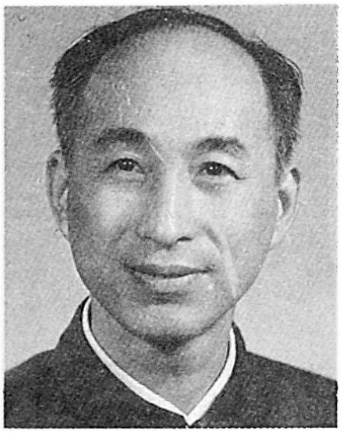
DOI: https://doi.org/10.5169/seals-13868

Studies on Aseismic Measures for a Large Existent Sluice Lock

Protection antisismique sur une grande écluse existante

Nachträglicher Erdbebenschutz für eine grosse Schleuse

Ming GAO,
Research Professor
China



Ming Gao, born in 1926, got his B.S. degree at the Jiao Tong University, Shanghai, China in 1947 and M.S. degree at Oklahoma State University, U.S.A. in 1956.

G.Y. DAI,
Senior Engineer
China

G.Y. Dai, born in 1936, got her B.S. degree in C.E. at the Dalian University of Science and Technology, Dalian, China in 1961.

SUMMARY

This paper presents a study on earthquake disaster reduction measures for a large sluice lock built during the late 1950s in Jiangsu, China and designed without seismic resistant capability. Field and laboratory dynamic tests were performed and a preliminary strengthening measure was taken. Field dynamic tests were performed again and a thorough three — dimensional numerical analysis taking into account structure-soil interaction and nonlinearity of the soil medium was made. Based on these studies, proposals and discussions for a better strengthening measure and rational analysis are put forward.

RÉSUMÉ

L'article présente une étude sur la limitation des effets des tremblements de terre pouvant agir sur une grande écluse à vannes, construite à la fin des années 50 sans aucune disposition antisismique. A la suite d'essais dynamiques effectués en laboratoire et sur place, l'écluse a été renforcée provisoirement, puis soumise à de nouveaux essais. Un calcul détaillé tridimensionnel a pris en compte l'interaction entre le sol et l'ouvrage, ainsi que la non-linéarité du matériau constituant le sol. En se basant sur les résultats acquis, les auteurs proposent de meilleures méthodes de renforcement et de calcul.

ZUSAMMENFASSUNG

Die folgende Studie betrifft die Erdbebenertüchtigung für eine grosse, schützenbetriebene Schleuse in Jiangsu, die Ende der fünfziger Jahre ohne jede Erdbebenvorkehrungen gebaut wurde. Nach dynamischen Labor- und Feldversuchen wurde sie provisorisch verstärkt und anschliessend von neuem getestet. Eine gründliche dreidimensionale Berechnung berücksichtigte die Boden-Bauwerk-Wechselwirkung und die ;Materialnichtlinearität des Bodens. Auf dieser Basis werden bessere Verstärkungsvorschläge und Berechnungsmethoden vorgeschlagen.

1. INTRODUCTION

Along with the occurrence of frequent strong earthquakes in China during the 1970s and the recognization of the probability of occurrence of very strong earthquakes near the lock site where the predicted intensity is IX to X in MM scale, a serial study aiming at strengthening the structure to raise its earthquake resistant capability of a large existent sluice lock located in the northen Jiangsu Province of China was carried out successively during the past 10 years. The lock which was built during the late 1950s designed at that time without consideration of seismic resistant capability is a reinforced concrete structure of 36 spans each 10m in length with a total length of 430m. Every 3 lock piers, one central pier and two side piers, together with the base slab forms a structural unit. The lock is situated on soil of medium stiffness with a predominant natural frequency around 3.3–3.9Hz. On the upper part of the lock, breast wall, highway bridge and operating bridge are constructed. The lock is a flood control and irrigation terminal of a large reservoir that controls an irrigation basin of over 0.2 million hectares in area. Therefore, the safety of the lock is a key problem in safeguarding district economic development and millions of lives.

During the late 1970s, field and laboratory dynamic tests and a 2–dimsnsional F. E. M. dynamic analysis were performed. Based on these studies, proposals for strengthening were put forward. Due to financial and some other reasons, a rather simple prelimnary strengthening measure was carried out. After the preliminary strengthening in the early 1980s, another field dynamic test was further carried out and a 3–dimensional F. E. M. dynamic analysis taking into consideration the structure–soil interaction and the nonlinearity of the soil medium was also performed. Further suggestions for strengthening and discussions on possible responses are made. In this paper, the abovementioned studies and analyses are presented.

2. FIELD AND LABORTORY DYNAMIC TESTS BEFORE PRELIMINARY STRENGTHENING

2.1 Field Dynamic Test

Resonant method was adopted for the field dynamic test with a 2t exciter. The fundamental natural frequency measured from the test is 4.8Hz for both the central pier and the side pier; the damping ratio is between 0.07~0.10 for the fundamental mode, the lateral flexural mode; and the amplification ratio of the pier top to the pier bottom is around 8~8.5. The second lowest frequency for lateral flexural mode measured is 17 Hz. The test result indicates that different piers of the structural unit vibrate simultaneously in phase as a unit although the breast wall and the piers are not rigidly connected and the central pier is thicker than the side piers.

2.2 Laboratory Dynamic Tests

2.2.1 Testing for Dynamic Characteristics of Different Structural Integrity

Plexiglass models in a scale of 1 to 50 were used in the testing for both the integrated structural unit and the single central pier. Sinuosoidal excitations applied in the testing

were carried out by both a small excitor and a medium–sized shaking table. In the testing for dynamic characteristics the following combinations of structural integrity were considered:
– (a), single central pier with a part of base slab only;
– (b), one integrated structural unit including 1 central pier, 2 side piers, the base slab and the breast wall between piers, but without superstructure;
– (c), one integrated structure unit with superstructure simply supported on the pier;
– (d), one integrated structure unit with superstructure semi–constrained to the pier;
– (e), same to (d), with 2 additional strengthening beams under the highway and the operating bridge between the pier;
– (f), same to (d), but with breast wall partially constrained to the pier.

The tested results are listed in Table 1, in which the results of field tests before preliminary strengthening are also listed for comparision. The values are all transformed into prototype according to the law of similitude. The first mode is the lateral flexural mode of the pier, the 2nd mode is the twisting mode of the pier, and 3rd mode is the second lateral flexural mode of the pier.

Item		Nat. Freq. (Hz)			Damping ratio 1st mode	Magnif. ratio top to bottom of pier
		1st mode	2nd mode	3rd mode		
Field test	Before strengthening	4.80–5.0		18.2–19.2	0.07–0.10	8.0–8.5
Model tests	Case a	4.0–4.1	8.7	16.6–19.3	0.027	
	Case b	4.1	6.2	10.5	0.074	
	Case c	3.9	8.5	14.8	0.189	7.2–8.4
	Case d	3.7	7.8	11.6		
	Case e	3.7	8.5	11.0		
	Case f	4.9	7.6	12.0	0.068	
3–D F.E. Analysis		4.88	5.04	6.10		

Table 1 Dynamic characteristics determined from the tests

2.2.2 Testing for the Interaction Effect Between Strurctural Units

Another model test for investigating the interaction effect between structural units was also performed. The tested results show that:
– the existence of side units do have some effect of reducing the responses although almost no effect for natural frequencies;
– a provision of stiff water proofing material in the expansion joint will have a beneficial effect in reducing the responses and increasing of fundamental natural frequency;
– a bigger I–section beam with a height of 4.20 m and flanges of 1 m, web of 0.30 m, in the downstream side between the piers can give more advantageous effect on the reduction of responses.

2.2.3 Analysis of the Tested Results

From the model tests it can be seen that:
- not too much differences in dynamic characteristics yield for various degree of integrity of the structure, the strengthening by only adding small connection beams under bridges will not be very effective;
- the natural frequencies measured for the case (f) in which breast walls are partially rigidly connected to the pier rise considerably and match the field test results, it seems that the actual connection between the breast wall and the pier approaches to the partially connected condition;
- a bigger beam similar to the breast wall under the highway bridge between the piers with similar constraint to the pier might not only reduce the twisting effect but also raise further the natural frequencies of the structure;
- stiffer waterproofing material in the expansion joint between the structural unit can also have some advantageous effect for the reduction of responses.

3. NUMERICAL ANALYSES

3.1 Dynamic Equilibrium Equation of the System

The analysis is based on the following assumptions:
- the reinforced concrete lock structure is in linear state;
- the soil under the structure is a continuum in linear or nonliear elastic state;
- the fluid is an ideal incompressible fluid.

Under earthquakes, the dynamic equilibrium equation of the system can be written as:

$$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}=-[M][I]\{\ddot{x}_g\} \tag{1}$$

where $\{x\}$, $\{\dot{x}\}$, $\{\ddot{x}\}$ are the displacement, velocity and acceleration vectors of the system respectively; $[M]$, $[C]$ and $[K]$ are the mass, damping and stiffness matrices of the system; $\{\ddot{x}_g\}$ is the input acceleration vector at the rock base; and $[I]$ is a unit transformation matrix. Natural frequencies and modal shapes of the system are first solved from the eigen equation. Proportional damping is assumed using the tested results.

3.2 3–Dimensional F. E. Dynamic Analysis

A 3–dimensional finite element dynamic analysis is carried out, taking into account the structure–soil interaction and the nonliearity of the soil medium. In the analysis, the pier, the base slab and the superstructures are discretized into plate elements, the soil medium is discretized into solid elements and the fluid is discretized into 3–dimensional fluid elements. ADINA program is adopted in the analysis, and for the time response analysis, Newmark $-\beta$ method is adopted.
From the analyses using various values of modulus of deformation of the soil medium and various ranges of soil medium with and without soil mass being considered, it can be seen that for the case taking $Es =$ 80 MPa with the range of soil medium equal to 40 × 36 × 12 m for one structural unit and the mass of soil medium not considered the

fundamental frequency is 4.88 Hz, closest to that from the field test as also shown in Table 1. However, for higher modes, the differences are large as in the space analysis natural frequencies of the soil medium and other structural elements are all included. Earthquake responses are evaluated taking into consideration the structure–soil interaction for linear and nonlinear soil medium. In the elastic condition, $Es = 80.0$ MPa is taken, and for the nonlinear condition, stress –strain relationship suggested by Hardin and Drneivich is adopted with slight modification with initial $Eso = 80.0$ MPa. EI Centro acceleration record with peak value regulated to 0.50 g is used for the input at the bottom of medium in the direction of cross current. The evaluated results for some key points are listed in Table 2.

Item	Point	Location	Analytical condition		
			Linear med.	Nonlinear med.	Rigid base
Max. diaplacement (cm)	10	Pier top mid.	1.13	1.61	0.618
	15	Pier top downstr.	1.11	1.60	1.067
	16	Pier top upstr.	1.14	1.61	0.847
Max. acce. (g)	10	Pier top mid.	0.810	0.765	0.444
	15	Pier top	0.891	0.759	0.369
	16	Pier top upstr.	0.824	0.765	0.572
Max. normal base stress (MPa)	1	Pier base upstr.	0.801	0.937	1.031
	4	Pier base middle	0.565	0.548	3.281
	7	Pier base downstr.	1.060	1.081	4.520

Table 2 Comparison of analytical responses for linear and nonlinear soil medium

From Table 2, it can be noticed that normal stresses at the base of pier are greatly reduced when deformation of soil medium is taken into account especially at the toe to only about 25% of the values for rigid base condition, although the maxium displacements and accelerations at top of pier both increased considerablly. This might be due to stress redistribution between the pier and the base slab as well as to the deformation of base slab in compliance to the deformation of soil medium. It can also be noticed that differences are not large between the values evaluated for linear and nonlinear soil medium.

4. STRENGTHENING MEASURES

4.1 Preliminary Strengthening Measure and Field Test After Preliminary Strengthening

Due to financial and other causes, a preliminary simple strengthening measure was taken. It includes 2 relatively small reinforced concrete T beams between the piers under the highway bridge and 1 even smaller steel truss beam under the operating bridge. After the preliminary strengthening, field test was again performed. It is found that the change of dynamic characteristics is insignificant, however the reduction of responses is noticable. The fundamental frequency raises from 4.8 to 4.90–5.15 Hz, the second mode frequency which is of the twisting mode of the pier and had not been identified in the previous field test is 8.4–8.6 Hz, and the third mode frequency which is the second flexural mode of the pier is 17.4–18.0 Hz. The damping ratios determined are between 0.06 to 0.112 for the first mode, 0.041–0.069 for the 2nd mode and 0.037 to 0.074 for the third mode. The displacement amplitudes reduce from 33% to 56% for various points tested. It seems that the preliminary strengthening yields a certain degree of effectiveness although not very ideal. Therefore a proposal for further strengthening is put forward.

4.2 Proposal for Further Strengthening

From the field tests, model tests and the numerical analysis made, a proposal for further strengthening is put forward:
A large connecting reinforced concrete beam similar to the breast wall at the upstream side of the lock in the downstream between the piers close to the haunches and partially rigidly connected to the pier for each structural unit is suggested to replace the present small connecting beam.
The larger beam will not only reduce significantly the twisting effect of the pier at the downstream side of the lock but will also significantly enlarge the difference between the fundamental natural frequency of the lock and the predominant frequency of the soil medium and thus reduce the magnification effect. Stiffer waterproofing material placed in the gaps between structural units might be benefiical to increasing damping ratio and reducing responses.

5. CONCLUDING REMARKS

Through the serial study, a comprehensive concept of the dynamic characteristics and earthquake resistant capability of the sluice lock is obtained, and a proposal is put forward for further strengthening.
As to the analysis, it is suggested that the lock, being a complicated structure, should be analyzed 3–dimensionally taking into consideration of structure–soil interaction if rational seismic responses are to be obtained, in which the soil medium can be taken to be elastic under earthquakes of medium intensity but better to be nonelastic if the intensity of earthquakes is large.

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